CAUSES OF CRACKING IN HIGH-STRENGTH
WELD METALS

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BATTELLE MEMORIAL INSTITUTE

AUGUST 1954

WRIGHT AIR DEVELOPMENT CENTER

NOTICE

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Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the Battelle Memorial Institute, under USAF Contract No. AF 33(038)-12619. The contract was initiated under Research and Development Order No. R615-20 (A-B), "Causes of Cracking in High-Strength Weld Metals", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Major L. P. Marking acting as project engineer.
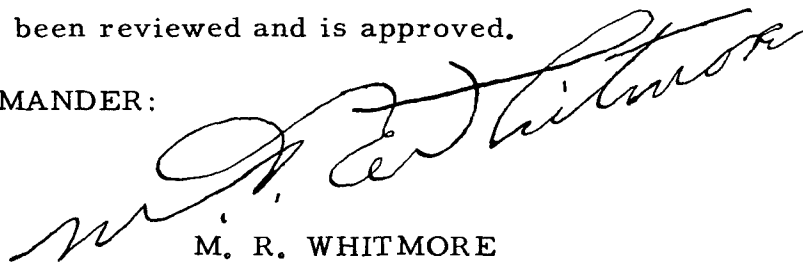
ABSTRACT

This report summarizes the third year of experimental work at Battelle on the causes of cracking in high-strength weld metals. During the period from August 12, 1953, to August 12, 1954, hot-tension and weld-metal cracking studies were conducted on SAE 43XX-type steels and other selected steels. Results from these studies showed a correlation, inasmuch as an increase in carbon, sulfur, and phosphorus tended to lower hot ductility and promote hot-crack susceptibility, and a misch metal addition seemed to have the opposite effects.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

LIST OF ILLUSTRATIONS

Causes of Cracking in High-Strength Weld Metals

This report summarizes work done during the fourth contract period from August 12, 1953, to August 12, 1954, on the causes of cracking in high-strength weld metals. The information obtained is valuable in devising preventatives for the cracking.

A literature survey was made during the first contract period. Very briefly, this indicated that the most common form of cracking in high-strength weld metals is hot cracking, which occurs because of poor strength and ductility as the weld deposit is cooling down to about 1500 F. During the second contract period, special apparatus was built to measure strength and ductility of the weld metals at high temperatures. At the same time, various weld-metal cracking tests were evaluated, because a correlation was sought between hot-tension and weld-metal cracking data. The third contract period was the proving-out period for the hot-tension apparatus, while hot-tension tests were conducted on high-purity and standard SAE 43XX-type steels as well as on two commercial high-strength weld-metal compositions. A suitable cracking specimen was developed, and the results from early tests on SAE 43XX-type steels were correlated with the results from hot-tension tests. These results indicated that a combined high sulfur-phosphorus content, even though within specifications, was harmful especially in respect to the hot-ductility and hot-cracking susceptibility of SAE 4340 steel. A high carbon content also lowered hot ductility and increased the hot-cracking tendency of SAE 43XX-type steels. A misch metal addition was found to have a slight beneficial effect on hot cracking.

This report discusses: (1) a continuation of hot-tension and cracking tests on SAE 43XX-type steels; and (2) hot-tension and cracking tests on six selected steels, two of which contain boron.

SUMMARY

Hot-tension and weld-metal cracking tests were conducted on a total of 19 different heats. Thirteen of these heats were SAE 43XX-type steels; four simulated a high-strength weld metal; and two were boron steels. The circular-patch and circular-groove specimens were re-evaluated in addition to continuing the restrained weld type of cracking test.

Hot-tension tests were made on six of the 13 SAE 43XX heats to check the effects of carbon and combined sulfur-phosphorus contents on hot strength and ductility. The other seven heats included four with misch metal. In all of these heats, the following elements were studied in respect

to hot-tension properties: carbon (0.20%, 0.33%, 0.45%, 0.59%), sulfur (0.008%, 0.015%, 0.036%), phosphorus (0.011%, 0.026%), and misch metal (0.015%, 0.20%). Carbon and especially phosphorus lowered hot strength and ductility. The SAE 4340 heat with 0.015 per cent sulfur was stronger and more ductile than the two heats with the other sulfur contents, thus suggesting that there is an optimum sulfur content for optimum hot-tension properties. Misch metal tended to raise hot strength and ductility slightly.

Hot-tension tests on the four heats simulating a high-strength weld metal also showed that high sulfur-phosphorus contents are detrimental to hot ductility. In addition, they showed that misch metal aids hot ductility. A boron steel with a composition like that of AISI 86B40, except for a misch metal addition, displayed excellent hot strength but poor ductility.

Restrained weld-cracking tests were conducted on the same heats studied in the hot-tension tests. The results indicated that a misch metal addition and decreased carbon, and especially decreased sulfur contents, increased hot-cracking resistance. The effect of phosphorus on hot cracking could not be determined from the heats available. The results obtained from restrained weld-cracking tests are consistent with hot-ductility data.

Circular-groove and circular-patch cracking tests were conducted on a few selected heats. The results from these tests are in partial agreement with the results from restrained weld tests and with each other. Besides being inconsistent, the test results do not reflect the high degree of sensitivity that is found in the restrained weld test. Another shortcoming of the circular-groove and circular-patch tests is that inspection of cracks in the weld metal is impossible, if it is desired to prove that the cracks formed at elevated temperatures. For the reasons stated, no further circular-groove or circular-patch tests were made.

In the next contract period, hot-tension and weld-metal cracking tests will be continued on high-strength steels in a study of phosphorus, silicon, and nitrogen. Low temperature or cold cracking also will be investigated by means of either impact or tension tests. Finally, the light-microscope study of nonmetallic inclusions in welds will be continued. The aid of microspectrographic analysis and radioactive isotopes will be enlisted in this study, if considered advisable.

HOT-TENSION TESTS

Hot-tension tests were conducted on 13 SAE 43XX-type heats, on four heats simulating a commercial high-strength weld metal, and on a boron steel simulating AISI 86B40. The tests on seven of the 13 SAE 43XX-type heats were check tests. The other six SAE 43XX-type heats studied were

new heats. A total of seven heats contained misch metal. Carbon, sulfur, and phosphorus variations, as well as differences in misch metal content, were investigated in relation to hot-tension properties.

Test Procedure

The hot-tension tests were made with the same apparatus described in the summary report dated August 12, 1953, except for two changes.

First, a 4-1/2-turn induction coil was used with a 40-kw Lepel spark-gap frequency-converter unit, instead of a slit-bar coil with a Tocco induction-heating unit. This change made it possible to obtain temperatures of the order of 3000 F, whereas, 2750 F was the previous peak temperature. All of the known inclusions in steel were believed to have melted at the higher temperature. The heating cycles for the two setups were almost identical. A typical cycle is shown in Figure 1.

The second change involved temperature measurement. Temperature was measured directly in the melted zones of the hot-tension specimen, rather than at a given distance from the melted zones with a calibrated thermocouple. The change from indirect to direct temperature measurements was expected to improve reliability. A platinum-platinum-rhodium thermocouple was used as before, except that it had to be protected by porcelain tubing, as shown in Figure 2.

The usual test procedure was followed. Specimens were heated to about 3000 F, then cooled to a predetermined temperature in the range from 2700 F to 1800 F, at which temperature they were fractured. The test results are presented and discussed below.

Tests on SAE 43XX-Type Steels

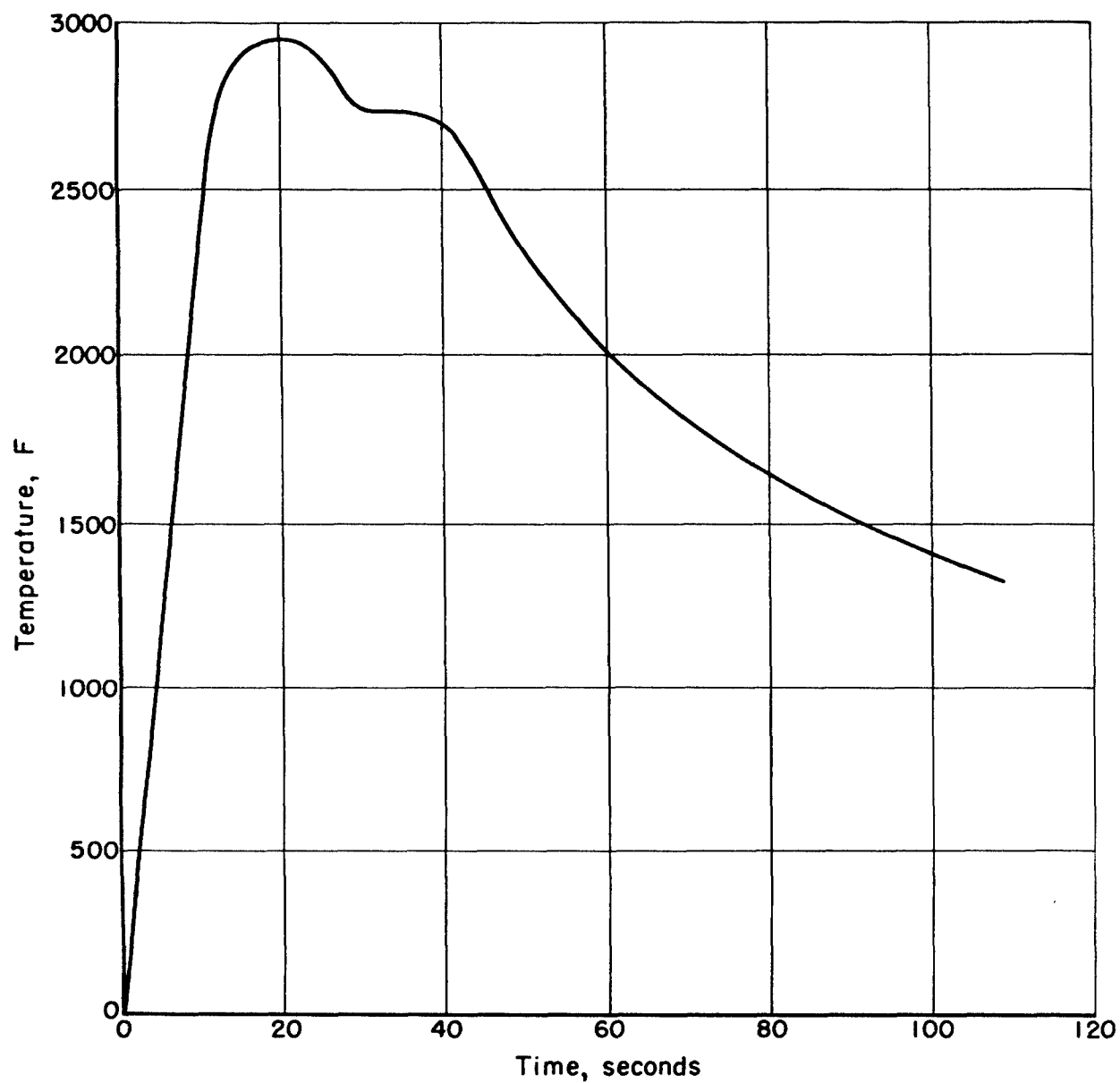The compositions of the 13 SAE 43XX-type heats tested are shown in Table 1.

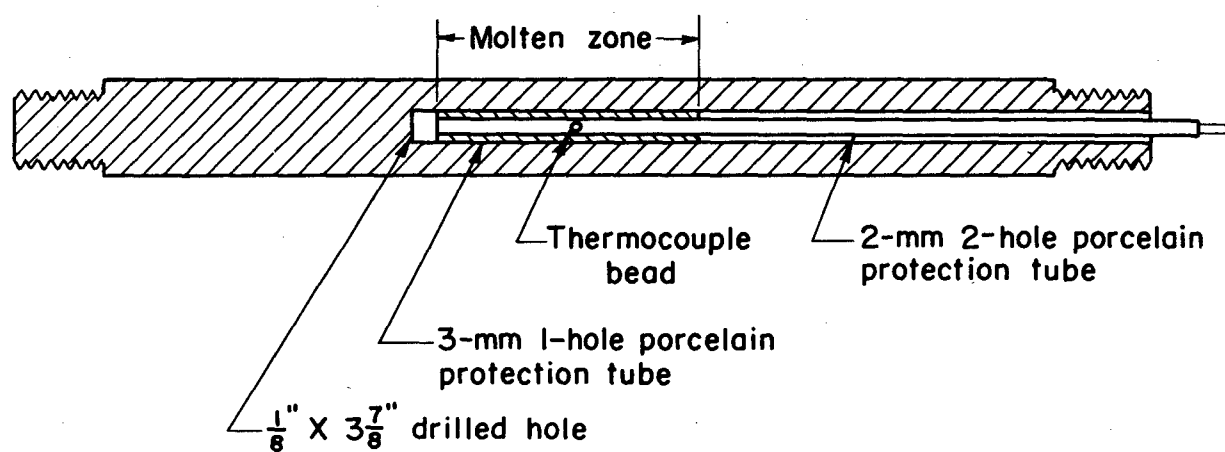FIGURE I. TYPICAL HEATING CYCLE USED IN HOT−TENSION TESTS

FIGURE 2. HOT-TENSION SPECIMEN IN WHICH TEMPERATURE IS
MEASURED IN THE MOLTEN ZONE

TABLE 1. COMPOSITION OF SAE 43XX-TYPE STEELS STUDIED IN
HOT-TENSION TESTS

Heat	C	Mn	Si	Ni	Cr	Mo	S	P
1	0.33	0.76	0.26	1.91	0.83	0.25	0.005	0.008
2	0.45	0.64	0.33	1.88	0.82	0.26	0.008	0.005
3	0.59	0.66	0.29	1.93	0.81	0.26	0.006	0.007
4	0.46	0.66	0.20	1.94	0.83	0.26	0.037	0.026
5	0.46	0.77	0.25	1.89	0.90	0.24	0.008	0.004
6	0.46	0.69	0.21	1.83	0.82	0.21	0.006	0.004
7[a]	0.45	0.72	0.07	1.92	0.88	0.24	0.006	0.007
11-A	0.40	0.76	0.22	1.84	0.83	0.24	0.015	0.012
11-B	As above, plus 3 pounds per ton of misch metal.							
12-A	0.35	0.77	0.23	1.84	0.81	0.23	0.036	0.011
12-B	As above, plus 3 pounds per ton of misch metal.							
1-H	0.20	0.67	0.30	2.07	0.91	0.39	0.008	0.010
3-H[b]	0.23	0.67	0.28	2.16	0.91	0.38	0.008	0.010

(a) 3 pounds per ton of misch metal added.

(b) 4 pounds per ton of misch metal added.

   The preparations of Heats 1 through 7 were described in the summary report dated August 12, 1952, and the results from initial tests on these heats were given in the last summary report dated August 12, 1953. After checking and supplementing the results, the data were plotted in Figures 6 and 7 of the progress report dated March 12, 1954. The curves are shown in subsequent figures of this report for comparison purposes. Heats 11 (11-A plus 11-B) and 12 (12-A plus 12-B) are 100-pound induction heats of SAE 4340 which were split into halves, one with misch metal (11-B and 12-B), the other without misch metal (11-A and 12-A). Heat 11, low in phosphorus (0.012% phosphorus) and intermediate in sulfur (0.015% sulfur), was made with electrolytic iron and other high-purity materials. Heat 12, also low in phosphorus (0.011% phosphorus) but high in sulfur (0.036% sulfur), was prepared from normal scrap and ferroalloy additions. Melting in the case of both Heats 11 and 12 was done in an MgO crucible under an argon gas blanket to limit oxidation and nitrogen pickup. No slag was used. Heats 1-H and 3-H are from a 15-ton basic electric heat of SAE 4320. Heat 3-H has a misch metal addition. Both heats are low in phosphorus (0.010% phosphorus) and sulfur (0.008% sulfur).

   Figures 3 through 6 include the results from tests on all the different SAE 43XX-type heats. The sulfur contents studied for comparison were: 0.008, 0.015, and 0.036 per cent; the phosphorus contents were 0.011 and 0.026 per cent; and the carbon contents were 0.20, 0.33, 0.45, and 0.59 per cent. The effects of various misch metal additions on the hot-tension properties of SAE 4340 and SAE 4320 are shown in Figures 3 and 4. The effects of varying the sulfur and phosphorus and carbon contents on hot strength and ductility are shown in Figures 7 and 8, respectively.

FIGURE 3. COMPARISON OF HOT STRENGTH AND DUCTILITY OF EXPERIMENTAL SAE 4340 STEEL SHOWING EFFECT OF MISCH-METAL ADDITION

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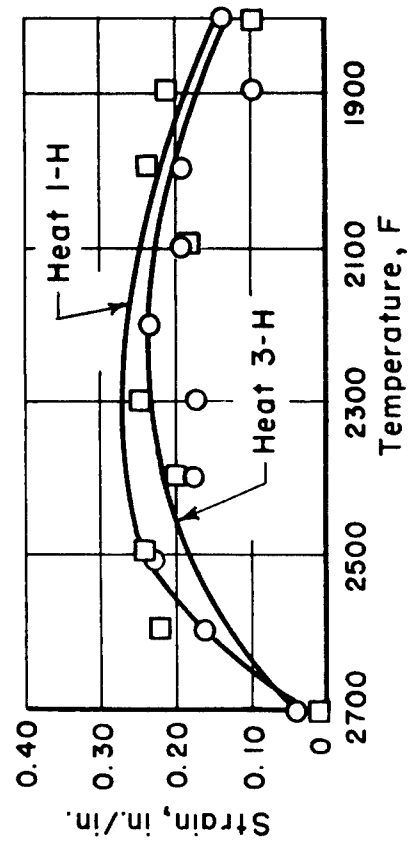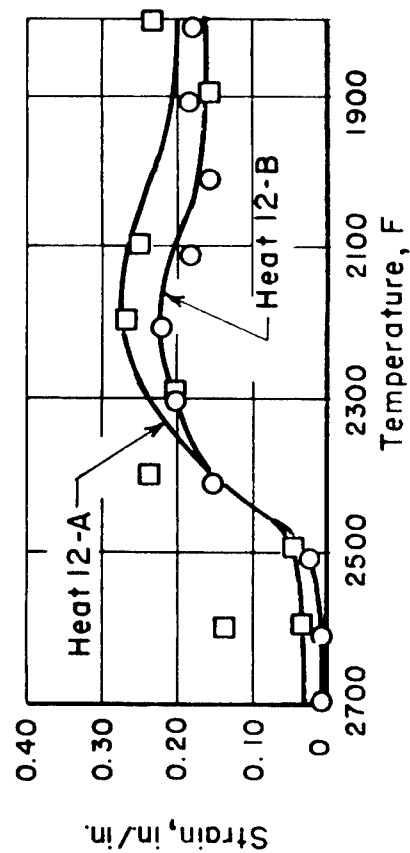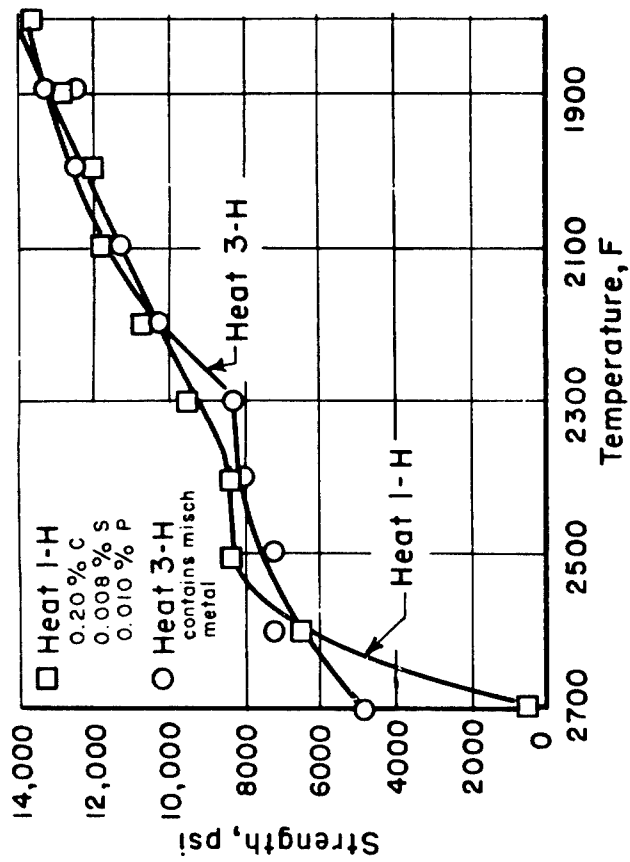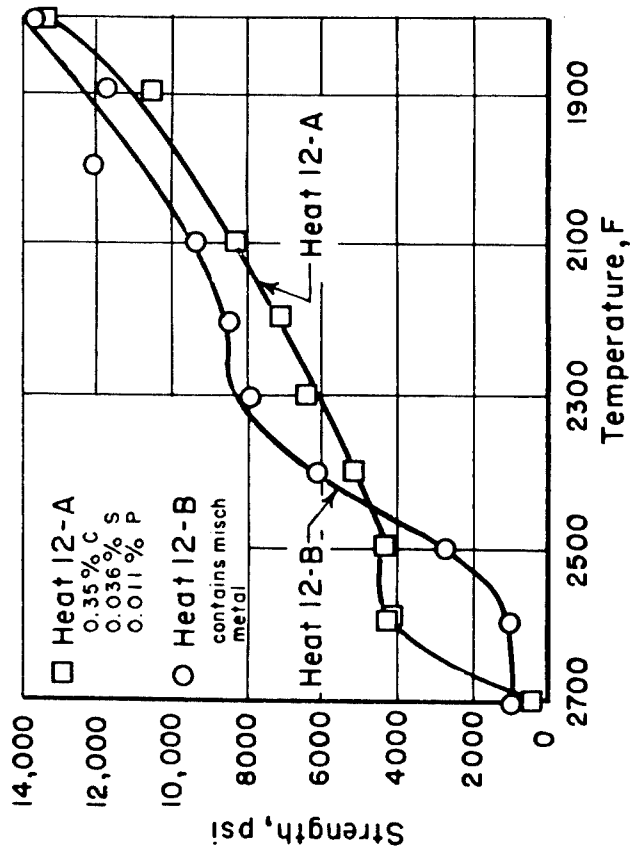
FIGURE 4. COMPARISON OF HOT STRENGTH AND DUCTILITY OF EXPERIMENTAL SAE 4340 (LEFT) AND SAE 4320 (RIGHT) STEELS SHOWING EFFECT OF MISCH-METAL ADDITION

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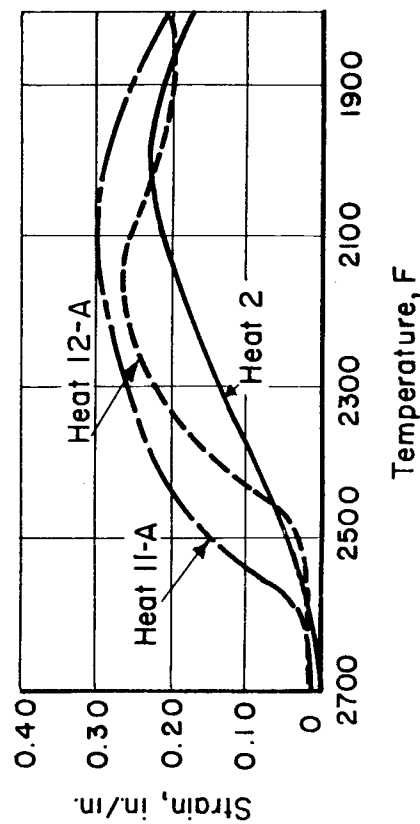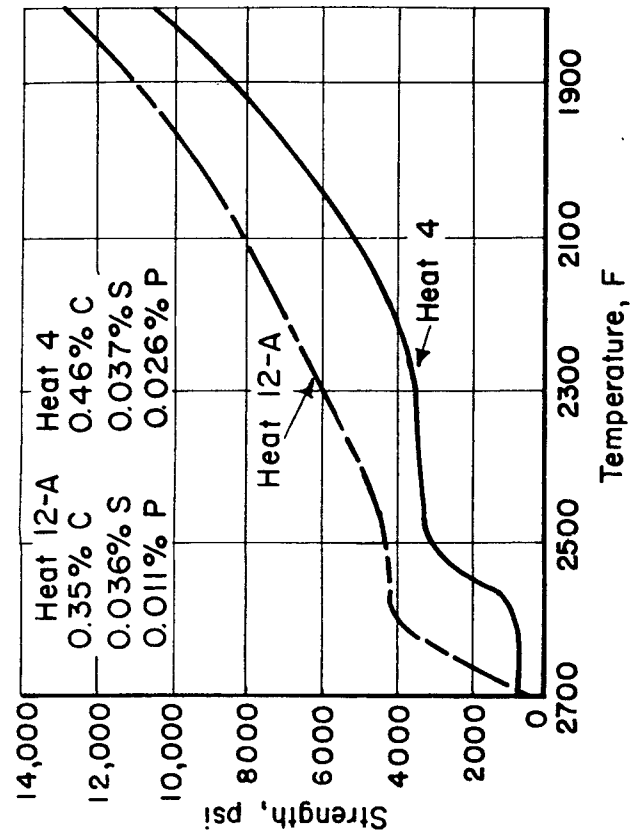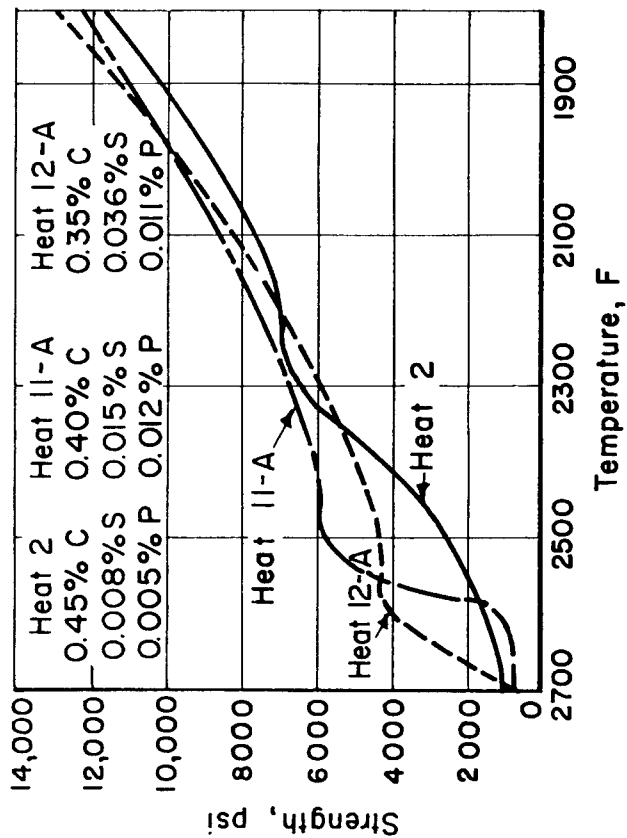
FIGURE 5. COMPARISON OF HOT STRENGTH AND DUCTILITY OF EXPERIMENTAL SAE 4340 STEELS
SHOWING EFFECT OF SULFUR (LEFT) AND PHOSPHORUS (RIGHT) CONTENTS
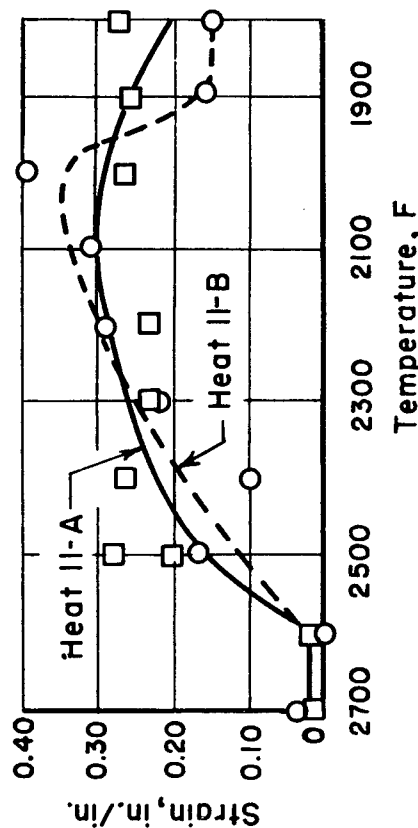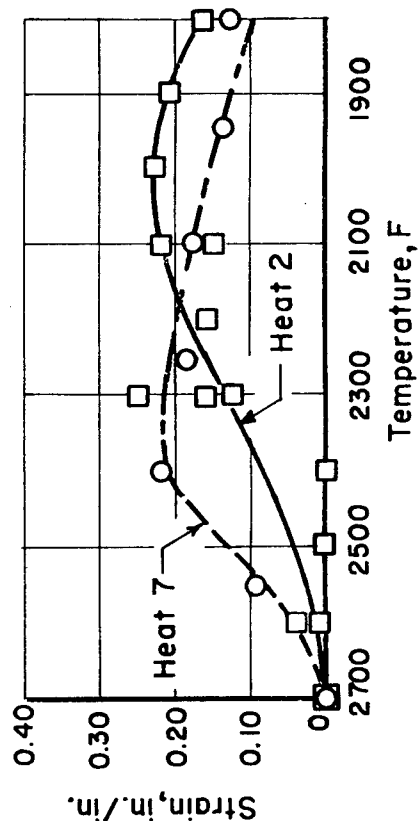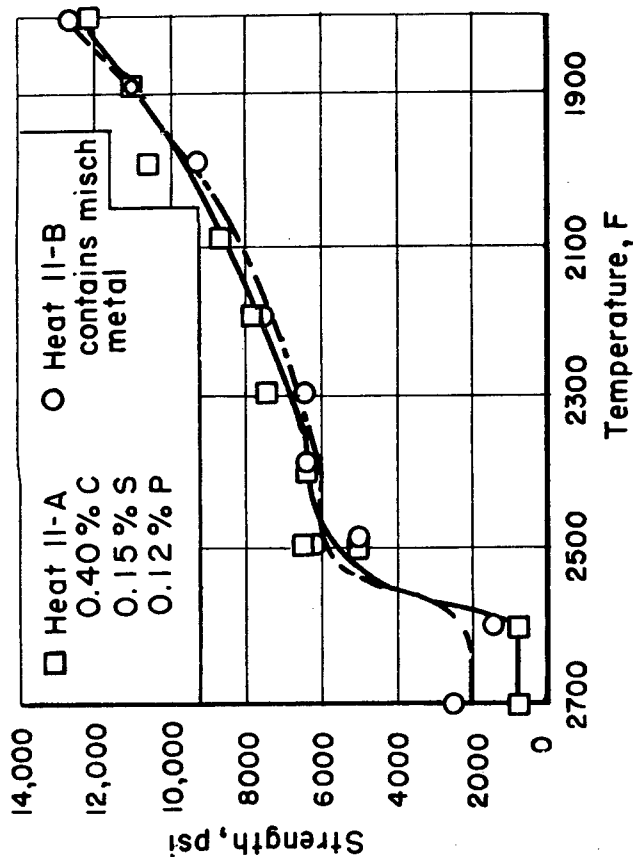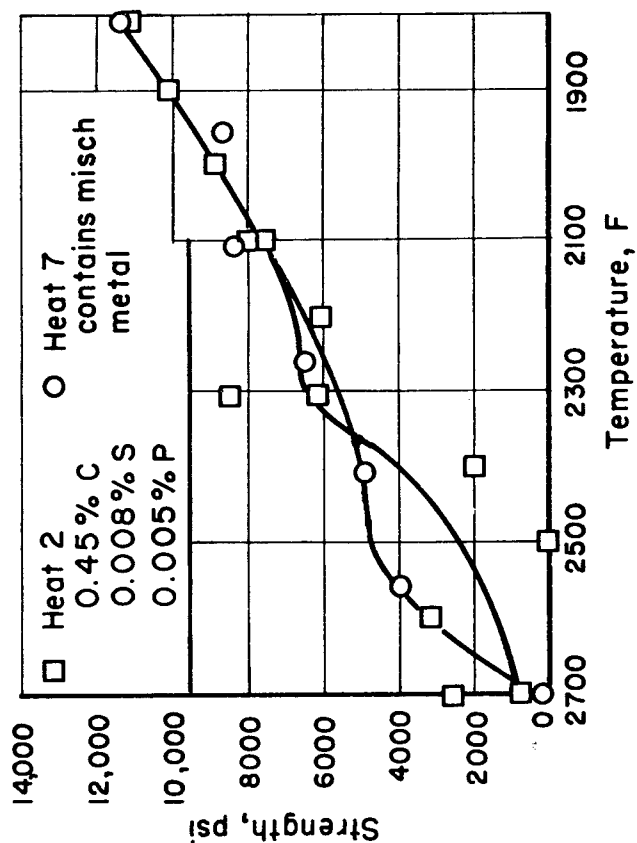
A-13970
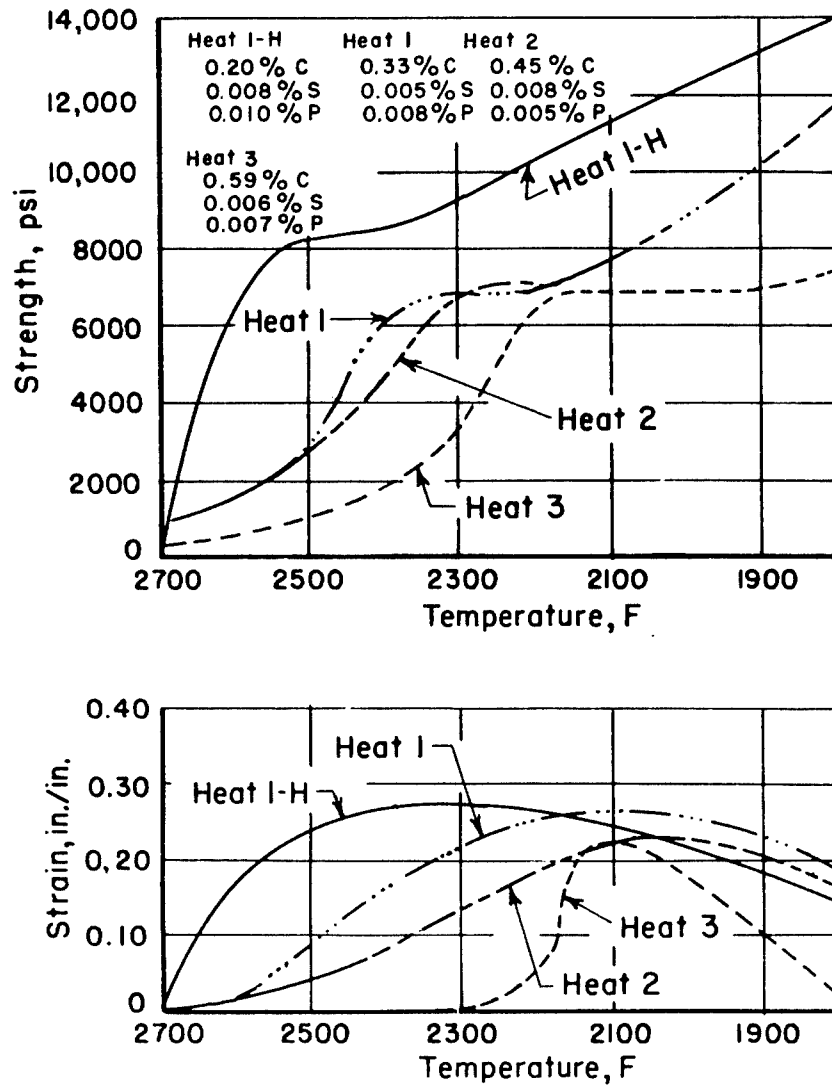
FIGURE 6. COMPARISON OF HOT STRENGTH AND DUCTILITY OF EXPERIMENTAL
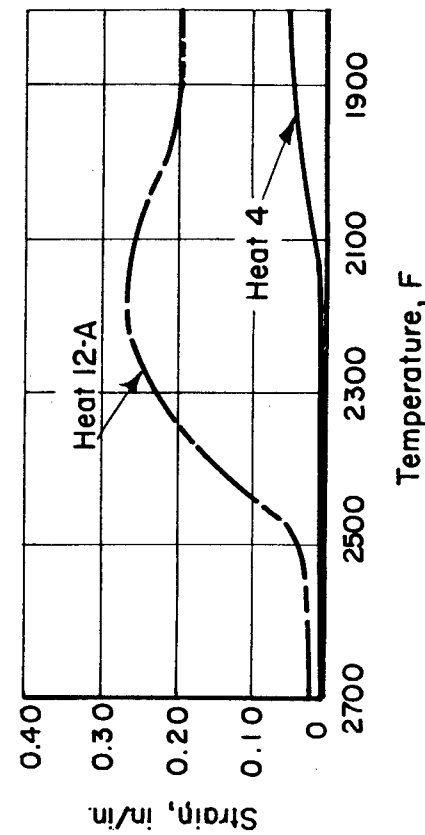SAE 43XX TYPE STEELS SHOWING EFFECT OF CARBON CONTENT

A-13969
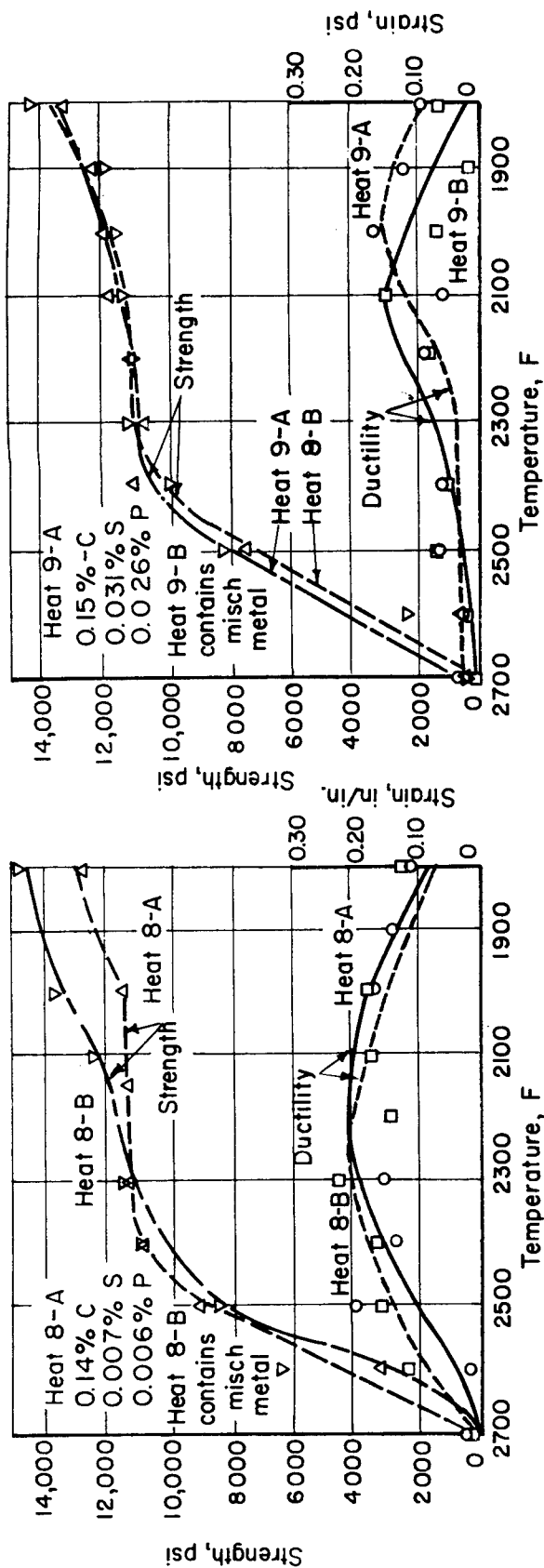
FIGURE 7. HOT-TENSION PROPERTIES OF HEATS SIMULATING A HIGH-STRENGTH WELD METAL
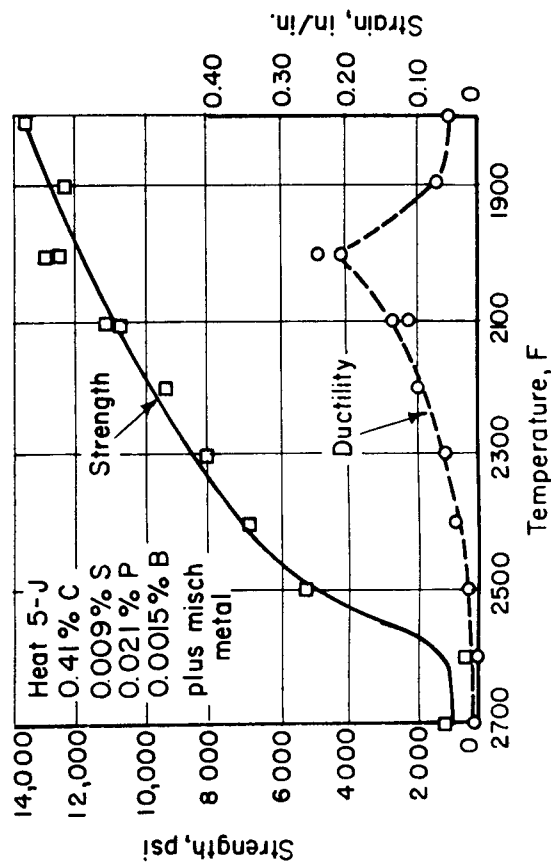
FIGURE 8. HOT-TENSION PROPERTIES OF AISI 86B40 STEEL HEAT CONTAINING MISCH METAL

A-13968

It was observed from Figures 3 and 4 that misch metal affected the hot strength and ductility in Heat 2 (low-sulfur-phosphorus SAE 4340) more than in Heats 11-A (intermediate sulfur, low-phosphorus SAE 4340), 12-A (high-sulfur, low-phosphorus SAE 4340), and 1-H (low-sulfur-phosphorus SAE 4320). A misch metal addition to Heat 2 (see curve for Heat 7): (1) increases hot ductility above a temperature of about 2150 F; (2) displaces the point of maximum ductility from a temperature of about 2000 F to a temperature of about 2350 F; and (3) increases hot strength above a temperature of about 2350 F. Misch metal additions to Heat 11-A (see curve for Heat 11-B) and to Heat 1-H (see curve for Heat 3-H) do not increase the strength or ductility below a temperature of about 2600 F; or an addition to Heat 12-A (see curve for Heat 12-B) below a temperature of about 2450 F.

The properties of Heats 2 (0.008% sulfur), 11-A (0.015% sulfur), and 12-A (0.036% sulfur) were compared (Figure 5, left) to show the effects of sulfur. Heats 2, 11-A, and 12-A are all low-phosphorus SAE 4340 heats. Increasing the sulfur content from 0.015 to 0.036 per cent causes a decrease in hot ductility, but has no significant effect on hot strength. Compared with Heats 11-A and 12-A, Heat 2 (0.008% sulfur) has unexpectedly poor strengths and ductility (see discussion).

A comparison of the properties of two high-sulfur SAE 4340 heats, 12-A (0.036% sulfur) and 4 (0.037 sulfur), which differ in phosphorus content, is shown in Figure 5 (right). It is noted also that these two heats differ in carbon content (Heat 12-A, 0.35% and Heat 4, 0.46%). However, it is believed that the difference in carbon is not so effective as the difference in phosphorus. The effect of carbon on the hot-tension and ductility properties of SAE 43XX steels is illustrated in Figure 6. Lowering the carbon content from 0.46% to 0.35% improved the hot strength and ductility, but the improvement in properties, especially ductility, was not so pronounced as the improvement shown by a decrease in phosphorus as shown in Figure 5 (right).

The dependence of the hot-tension properties of SAE 43XX-type steel on carbon content is shown in Figure 6. Curves are presented for Heats 1-H (0.20% carbon), 1 (0.33% carbon), 2 (0.45% carbon), and 3 (0.5% carbon,) all of which are low sulfur (0.008% or less sulfur) and phosphorus (0.010% or less phosphorus). The chief effect of increasing carbon from 0.20 to 0.59 per cent is to lower hot strength and ductility. A related result of increasing the carbon content is the general displacement of maximum ductility to a lower temperature.

Tests on Selected Steels

The compositions of the five remaining heats studied during this work period are shown in Table 2.

TABLE 2. COMPOSITION OF SELECTED STEELS STUDIED IN HOT-TENSION TESTS

Heat	Chemical Composition, per cent								
	C	Mn	Si	Ni	Cr	Mo	S	P	Other
8-A	0.14	0.88	0.55	1.77	1.00	1.00	0.007	0.006	0.19V
8-B	As above, plus 3 pounds per ton of misch metal.								
9-A	0.15	0.78	0.51	1.73	0.93	1.03	0.031	0.026	0.19V
9-B	As above, plus 3 pounds per ton of misch metal.								
5-J[a]	0.41	0.91	0.28	0.51	0.53	0.24	0.009	0.021	0.0015B

(a) 2-1/2 pounds per ton of misch metal added; original sulfur content was 0.022%. Material was supplied by Metallurgy Department, Carnegie Institute of Technology.

Heats 8-A, 8-B, 9-A, and 9-B simulate a high-strength weld metal deposited with a coated electrode. Heat 5-J is similar to the boron steel AISI 86B40. Heats 8 (8-A plus 8-B) and 9 (9-A plus 9-B) are 200-pound induction heats, half of each contains misch metal (Heats 8-B and 9-B). The low-sulfur low-phosphorus Heat 8 was prepared from electrolytic iron and other high-purity materials, whereas ordinary scrap and ferroalloy additions were the starting materials for Heat 3. Melting was done in an MgO crucible under an argon gas blanket. No slag was used. Heat 5-J, which is low in sulfur (0.009%), high in phosphorus (0.021%), and contains misch metal, is from a 50-ton basic electric heat.

The hot-tension properties of Heats 8-A and 8-B are plotted in Figure 7, left, and those of Heats 9-A and 9-B in Figure 7, right. The properties of Heat 5-J are shown in Figure 8.

Reference to Figure 9 indicates that either a reduction in sulfur and phosphorus contents, or a misch metal addition, is capable of: (1) increasing hot ductility; and (2) raising the temperature of maximum ductility, which may be related to the solidus temperature. The misch metal addition increases ductility above a temperature of about 2100 F. It does not seem to be quite so effective in increasing ductility or raising the temperature of maximum ductility, as is a reduction in sulfur and phosphorus, which was the finding in tests on SAE 43XX-type steels. Test results from the heat simulating AISI 86B40 steel (5-J) are shown in Figure 8. This heat appears to have excellent hot strength but poor hot ductility. No hot-tension tests were conducted on the AISI 81B30 heat (Heat 404, Table 3) studied in restrained weld tests. Typical analyses of deposits made with the inert-gas-shielded metal-arc consumable-electrode process of the experimental filler wire Heat 404 (as reported by WADC) showed variable phosphorus and somewhat higher silicon, but otherwise the chemical composition was within the specified range. It was planned to machine these specimens from weld metal deposited with AISI 81B30-type filler wire; however, the desired quantity of Heat 404 wire to conduct the tests could not be obtained.

Discussion of Test Results

The beneficial effects of misch metal on hot strength and ductility were not so great as it was hoped they would be from experience in the castings industry. It has been postulated that hot ductility depends on the type of inclusion formed between misch metal and sulfur, which in turn is supposed to depend on the ratio of misch metal to sulfur. At least four types of inclusions have been established[1]. No relation has been established between hot ductility and the ratio of misch metal to sulfur in this study, as is shown in the tabulation below:

Heat	Misch Metal Content, lb/ton	Misch Metal, %	Sulfur, %	Ratio of Misch Metal to Sulfur
7	3	0.15	0.006	25.0
11-B	3	0.15	0.015	10.0
12-B	3	0.15	0.036	4.2
3-H	4	0.20	0.008	25.0
8-B	3	0.15	0.007	21.4
9-B	3	0.15	0.031	4.8

Not only is the ratio of misch metal to sulfur widely different for Heats 7 (25.0), 8-B (21.4), and 9-B (4.8), in which misch metal was most effective, but the ratio varies widely for the other heats, 11-B (10.0), 12-B (4.2), and 3-H (25.0), in which misch metal was not so effective. Thus, there is no apparent reason, at present, for the inconsistent behavior of misch metal.

For the first time since the hot-ductility studies were started, it seems that there is no simple relationship between sulfur content and hot ductility, at least for sulfur contents less than 0.015 per cent. It was observed that an SAE 4340 heat with 0.008 per cent sulfur (Heat 2) possessed poorer ductility than two SAE 4340 heats with 0.015 per cent (Heat 11-A) and 0.036 per cent (Heat 12-A), respectively. In other words, there seems to be an optimum sulfur content at which hot ductility is a maximum. Perhaps there would be no advantage in reducing sulfur below this optimum, in order to counteract hot cracking.

Also, for the first time, it appears that the role of phosphorus as a causative agent in hot cracking is a real one. However, the exact role of phosphorus is unknown. There are several possibilities. For example, phosphorus may form eutectic or brittle constituents, such as nickel phosphide (Ni_2P, mp 2035 F), iron phosphide (Fe_3P, mp 2010 F), and a solid solution of phosphorus in iron plus iron phosphide (mp 1920 F). Segregated

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(1) Boulger, F. W., Martin, H. L. Sims, C. E., First and Second Progress Reports on "Deoxidation and Desulfurization of Cast Steel With Misch Metal", Battelle Memorial Institute, March 10, 1952, and October 30, 1952.

phosphorus may be identified by a phosphorus print or by etching. However, this method may not detect the small amount of phosphorus which is believed to contribute to hot cracking. One investigator[1] suggests that phosphorus plays an indirect role by affecting the segregation of sulfur. Another investigator[2] states that phosphorus, when present in ferritic weld metal (deposited with AWS Class E6010, E6012, or E6020 electrodes), up to 0.28 per cent does not cause hot cracking. Others place this limit at 0.15[3] and 0.07[4] per cent, respectively.

Other phosphorus contents (under 0.040 per cent) will be studied in hot-tension tests on SAE 43XX-type steels. The sulfur content of these steels will be kept low. Following these tests, a study will be made of the combined effects of different sulfur to phosphorus ratios.

WELD-METAL CRACKING TESTS

Three types of cracking tests were made to determine whether or not the results could be correlated with the results from hot-tension tests. The restrained weld specimen, the development of which was discussed in the summary report dated August 12, 1953, was used for all experimental heats, because it reproduced consistent results in earlier work. Circular-groove and circular-patch specimens were tried with a limited number of heats. The objective was to see how the results compared with the results from restrained weld tests.

Preparation of Welding Wire

All weld-metal cracking tests were conducted using the inert-gas consumable-electrode process. The wire for this process was prepared at Battelle. The experimental heats were reduced to 1/4-inch rounds by hot rolling. These, in turn, were cold drawn down to 3/32 inch, the size used in the tests. Frequent stress reliefs were required during the drawing operation, which took either one of two forms: (1) a furnace anneal in vacuo, to minimize contamination; or (2) short-time tempering in air by means of a welding generator. Tempering proved to be much more economical than annealing. A chemical analysis of the wires showed that there was no pickup of impurities during the tempering treatment.

(1) Rollason, E. C., and Roberts, D. F. T., "An Explanation of Hot Cracking of Mild Steel Welds", Trans. Inst. Welding - Welding Research - BWRA, 4 (6), 129r-132r (December, 1950).

(2) Claussen, G. E., "Adams Lecture - The Metallurgy of Covered Electrode Weld Metal", Welding Journal, 28, 12-24 (January, 1949).

(3) Spraragen, W., and Claussen, G. E., "The Effect of Phosphorus on the Welding of Steel - A Review of the Literature to July 1, 1937", Welding Journal, 18, 123s-130s (April, 1939).

(4) Helin, E., and Svantesson, Sven, "The Cracking Tendency of Welds Proper With Special Reference to Chemical Composition of Structural Steel", Trans. Inst. Welding (London), 3, 14-29 (1940).

Two series of restrained weld tests were conducted. In the first series, SAE 43XX-type steel wire was deposited in base plate of the same composition. In the second series, (a) wire from the four heats (see Table 2, Heats 8-A, 8-B, 9-A, and 9-B) simulating a high-strength weld metal was deposited in low- and high-sulfur SAE 4340 steel base plate; (b) low-sulfur SAE 4340 wire, with and without misch metal, was deposited in high-sulfur SAE 4340 base plate; and (c) wire from an AISI 81B30 heat and a heat simulating AISI 86B40 was deposited in base plate of the same or nearly the same composition. Compositions of heats used in the restrained weld tests, which are not shown in Tables 1 and 2, are shown in Table 3.

TABLE 3. COMPOSITION OF HEATS STUDIED IN RESTRAINED WELD-CRACKING TESTS[a]

| Heat | Chemical Composition, per cent | | | | | | | | |
	C	Mn	Si	Ni	Cr	Mo	S	P	Other
4-A	0.40	0.70	0.24	1.85	0.80	0.25	0.034	0.032	--
C	Commercial SAE 4340 steel containing 0.008 per cent sulfur.								
10-A	0.45	0.79	0.27	1.79	0.84	0.24	0.004	0.006	--
10-B	As above, plus 3 pounds per ton of misch metal.								
404	0.36	0.85	0.49	0.20	0.43	0.11	0.015	0.076[b]	0.004B
Commercial AISI 81B30	0.33	0.99	0.28	0.32	0.49	0.15	0.013	0.017	0.002B

(a) See also Tables 1 and 2.

(b) Analysis of weld deposit made with Heat 404 wire in commercial 81B30 base plate.

Tests were carried out under the same conditions described in the summary report dated August 12, 1953. In addition, a 200 F preheat was used successfully in all tests to prevent cold cracking. After welding, the weld joints (Figure 9) were fractured in a bending press and all cracks examined for the blue temper color which characterizes a hot crack.

The results of the first series of tests on SAE 43XX-type steels are shown in Table 4 and plotted in Figures 10, 11, 12, and 13. The indications are that: (1) increasing the carbon content of low-sulfur-phosphorus SAE 43XX-type steel in the range from 0.20 to 0.59 per cent causes a moderate

FIGURE 9. RESTRAINED WELD—CRACKING SPECIMEN

A-7735

TABLE 4. RESULTS OF RESTRAINED WELD-CRACKING TESTS ON SAE 43XX-TYPE STEELS

Heat	Number of Tests at Various Inches of Restraint													Minimum Level of Restraint to Develop Hot Cracks, inches
	2	2-1/2	3	3-1/2	4	4-1/2	5	5-1/2	6	6-1/2	7	7-1/2	8	
1	--	--	--	--	--	--	--	--	--	--	--	--	2	$>8^{(a)}$
2	--	--	--	--	1	--	--	--	--	--	--	2	2	8
3	--	--	--	--	--	--	--	--	1	2	3	1	--	7
4	2	--	--	--	1	--	--	--	--	--	--	--	--	$\leq 2^{(a)}$
7	--	--	--	--	--	--	--	--	--	--	--	--	2	$>8^{(a)}$
11-A	--	--	--	--	--	--	2	1	1	--	--	--	--	5-1/2
11-B	--	--	--	--	--	--	--	2	2	2	1	--	--	6
12-A	1	--	--	--	--	--	--	--	--	--	--	--	--	≤ 2
12-B	1	2	1	1	1	--	--	--	--	--	1	--	1	≤ 2
1-H	--	--	--	--	--	--	--	--	--	--	--	--	2	>8
3-H	--	--	--	--	--	--	--	--	--	--	--	2	2	8

(a) Two and 8 inches represent the lower and upper levels of restraint, respectively.
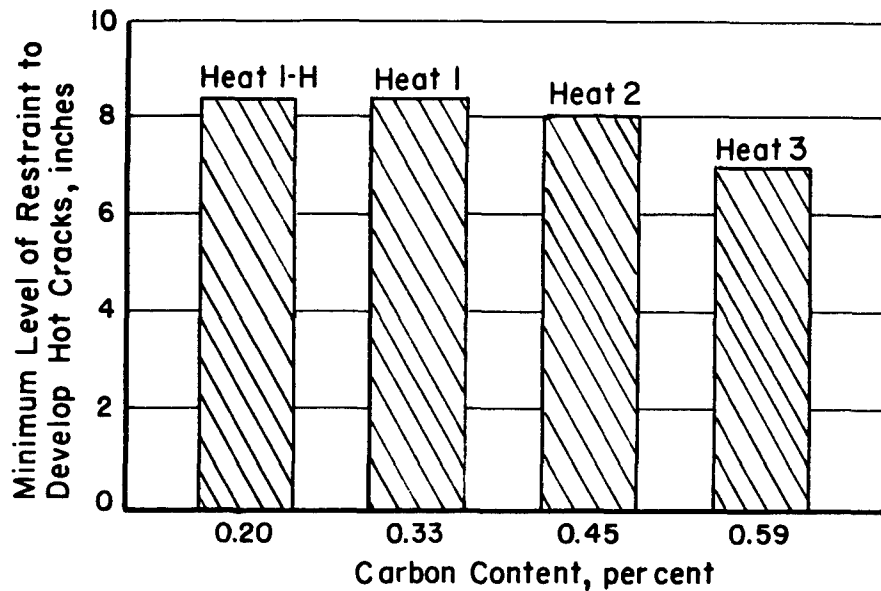
FIGURE 10. EFFECT OF CARBON CONTENT ON HOT-CRACK SUSCEP-
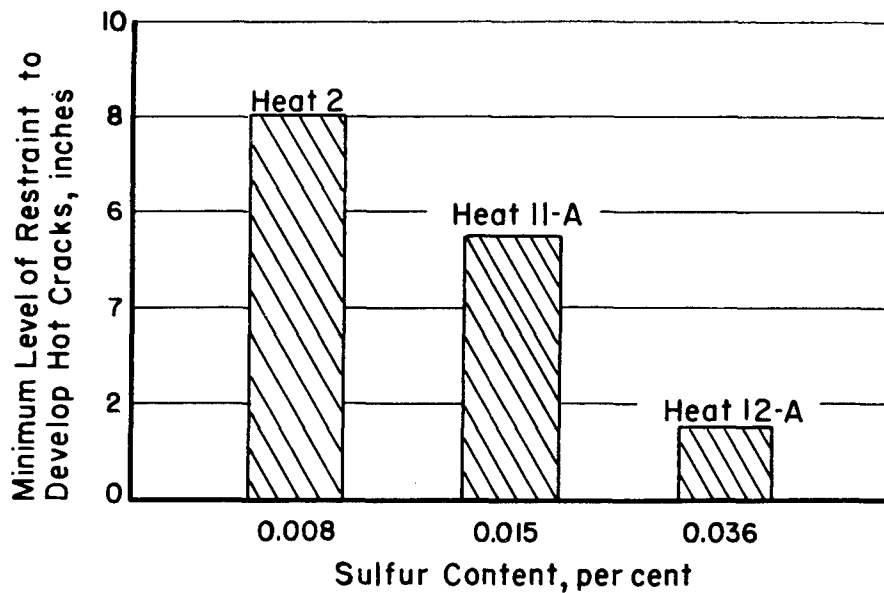TIBILITY OF LOW-SULFUR-PHOSPHORUS SAE 43XX TYPE
STEELS

FIGURE 11. EFFECT OF SULFUR CONTENT ON HOT-CRACK SUSCEP-
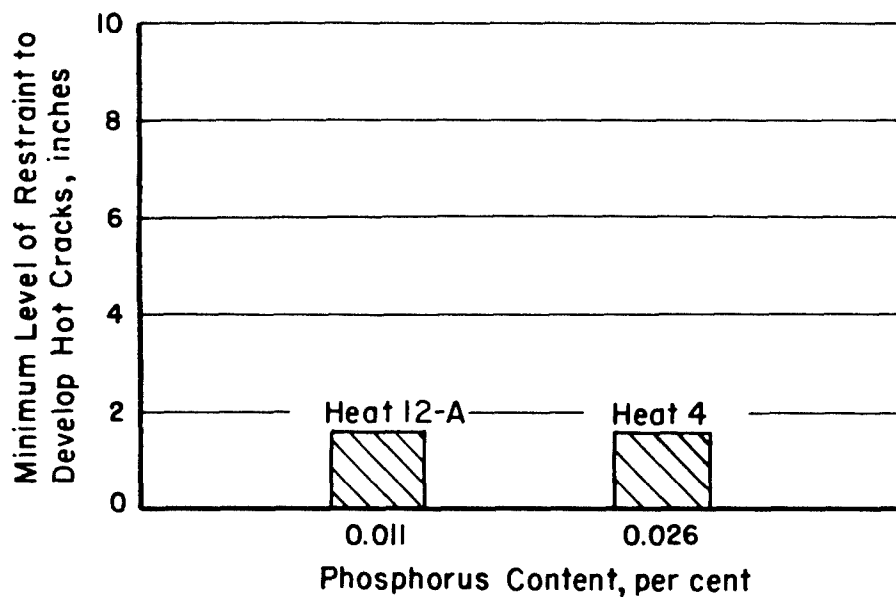TIBILITY OF LOW PHOSPHORUS SAE 4340 STEELS

A-13965

FIGURE 12. EFFECT OF PHOSPHORUS CONTENT ON HOT-CRACK SUSCEP-
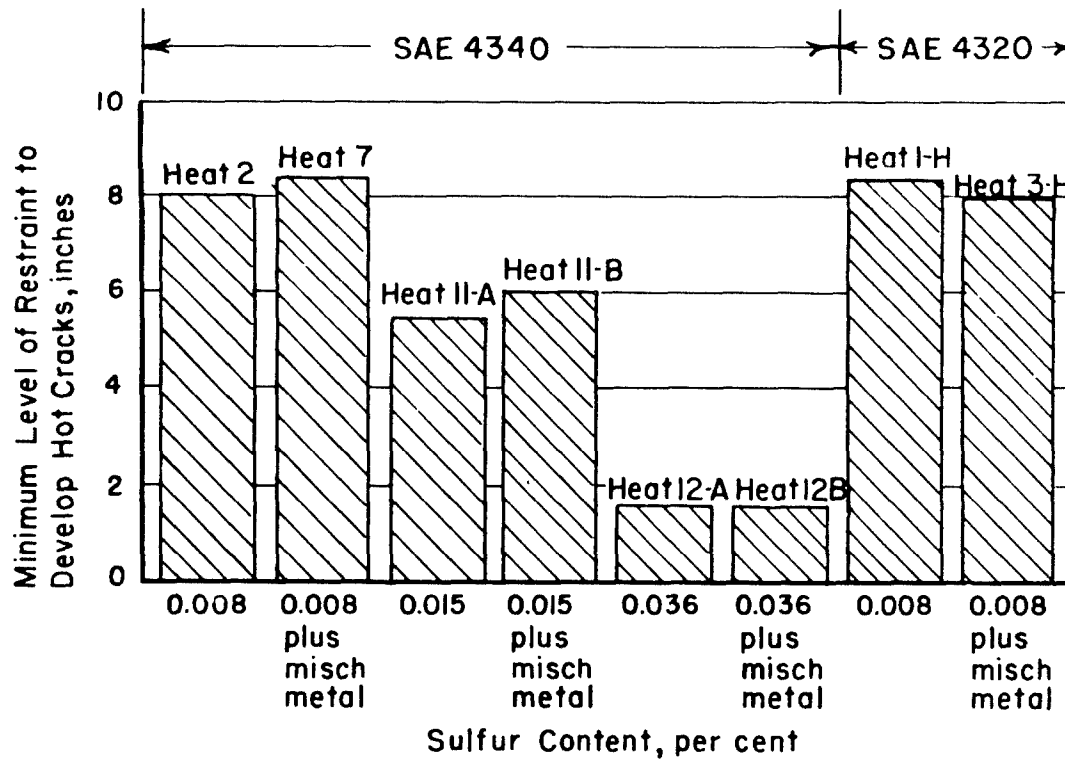TIBILITY OF HIGH-SULFUR SAE 4340 STEELS

FIGURE 13. EFFECT OF MISCH-METAL ADDITION ON HOT-CRACK SUSCEP-
TIBILITY OF LOW-PHOSPHORUS SAE 43XX-TYPE STEELS

A-13967

decrease in cracking resistance (Figure 10); (2) increasing the sulfur content of low-phosphorus SAE 4340 steel in the range from 0.008 to 0.036 per cent results in a pronounced decrease in cracking resistance (Figure 11); and (3) a misch metal addition to low-phosphorus SAE 43XX-type steels tends to increase cracking resistance (Figure 13). The effect of increasing the phosphorus content of <u>high-sulfur</u> SAE 4340 from 0.011 to 0.026 per cent is not clear from Figure 12 because both low- and high-phosphorus heats, 12-A and 4, respectively, have such poor cracking resistance. Further tests on <u>low-sulfur</u> heats are in order.

The results of the second series of tests are listed in Table 5 and plotted in Figure 14. These results indicate that: (1) the weld deposits made with low-carbon-sulfur-phosphorus filler wires (Combinations 2, 4, 1, and 3) are most crack resistant, whether they are in low- or high-sulfur-phosphorus SAE 4340 base plate; (2) the low-carbon high-sulfur-phosphorus filler wires (Combinations 5, 8, 6, and 7) have poor resistance to hot cracking, whether they are deposited in low- or high-sulfur-phosphorus SAE 4340 base plate; (3) the low-sulfur-phosphorus SAE 4340 welds deposited in high-sulfur-phosphorus SAE 4340 base plate (Combinations 9 and 10) have very poor crack resistance; (4) low-sulfur-phosphorus welds made in high-sulfur-phosphorus base plate (Combinations 1 and 3) are more crack resistant than high-sulfur-phosphorus welds made in low-sulfur-phosphorus base plate (Combinations 9 and 10); (5) a misch metal addition in a low- or high-sulfur filler wire showed little effect on cracking resistance in these tests; and (6) the two boron steels (AISI 81B30 and the heat simulating AISI 86B40, Combinations 11 and 12, respectively) have relatively poor resistance to hot cracking.

In view of the excellent performance of low-sulfur-phosphorus SAE 4340 filler wire when deposited in base plate of the same composition (Table 4, Heat 2), the poor cracking resistance of this filler wire when deposited in high-sulfur-phosphorus SAE 4340 (Table 5, Combinations 9 and 10) was quite surprising. Selected welds were analyzed for sulfur, and it was found that the welds contained about 0.020 instead of 0.005 per cent sulfur. The poor cracking resistance was probably due to this extensive dilution.

The reason for one other result is not immediately apparent. That is, low-sulfur-phosphorus welds made in high-sulfur-phosphorus base plate seem to be more crack resistant than high-sulfur-phosphorus welds made in low-sulfur-phosphorus base plate. This may be because there is less chance for sulfur to segregate in the center of the low-sulfur-phosphorus weld than in the center of the high-sulfur-phosphorus weld. The center of the weld is the last portion of the weld to solidify; therefore, the low-melting sulfides would tend to segregate to this area. Hot cracking occurred most often in the center of the weld deposit.

TABLE 5. RESULTS OF RESTRAINED WELD-CRACKING TESTS ON SELECTED STEELS

| Combi-nation	Heat[a] Filler Wire	Heat[a] Base Plate	Number of Tests at Various Inches of Restraint 2	2-1/2	3	3-1/2	4	4-1/2	5	5-1/2	6	6-1/2	7	7-1/2	8	Minimum Level of Restraint to Develop Hot Cracks, inches
1	8-A	4-A	--	--	--	--	--	--	2	1	--	1	1	--	--	5-1/2
2	8-A	C	--	--	--	--	--	--	--	1	--	--	--	--	1	>8
3	8-B	4-A	--	--	--	--	--	--	2	2	1	1	--	1	--	5-1/2
4	8-B	C	--	--	--	--	--	--	--	--	--	--	--	--	1	>8
5	9-A	4-A	2	1	--	--	--	--	--	--	--	--	--	--	--	2-1/2
6	9-A	C	1	1	--	1	--	--	--	--	--	--	--	--	--	≤2
7	9-B	4-A	1	1	1	--	--	--	--	--	--	--	--	--	--	≤2
8	9-B	C	2	2	2	1	1	--	--	--	--	--	--	--	--	2-1/2
9	10-A	4-A	2	1	1	1	1	--	1	--	--	1	--	--	--	2-1/2
10	10-B	4-A	1	1	1	1	1	1	--	1	--	--	1	--	--	≤2
11	404	Commercial AISI 81B30	--	--	1	1	1	--	1	1	1	--	--	--	--	3-1/2
12	5-J	5-J	2	2	1	--	1	--	--	--	--	--	1	--	--	≤2

(a) Chemical compositions given in Tables 1, 2, and 3.
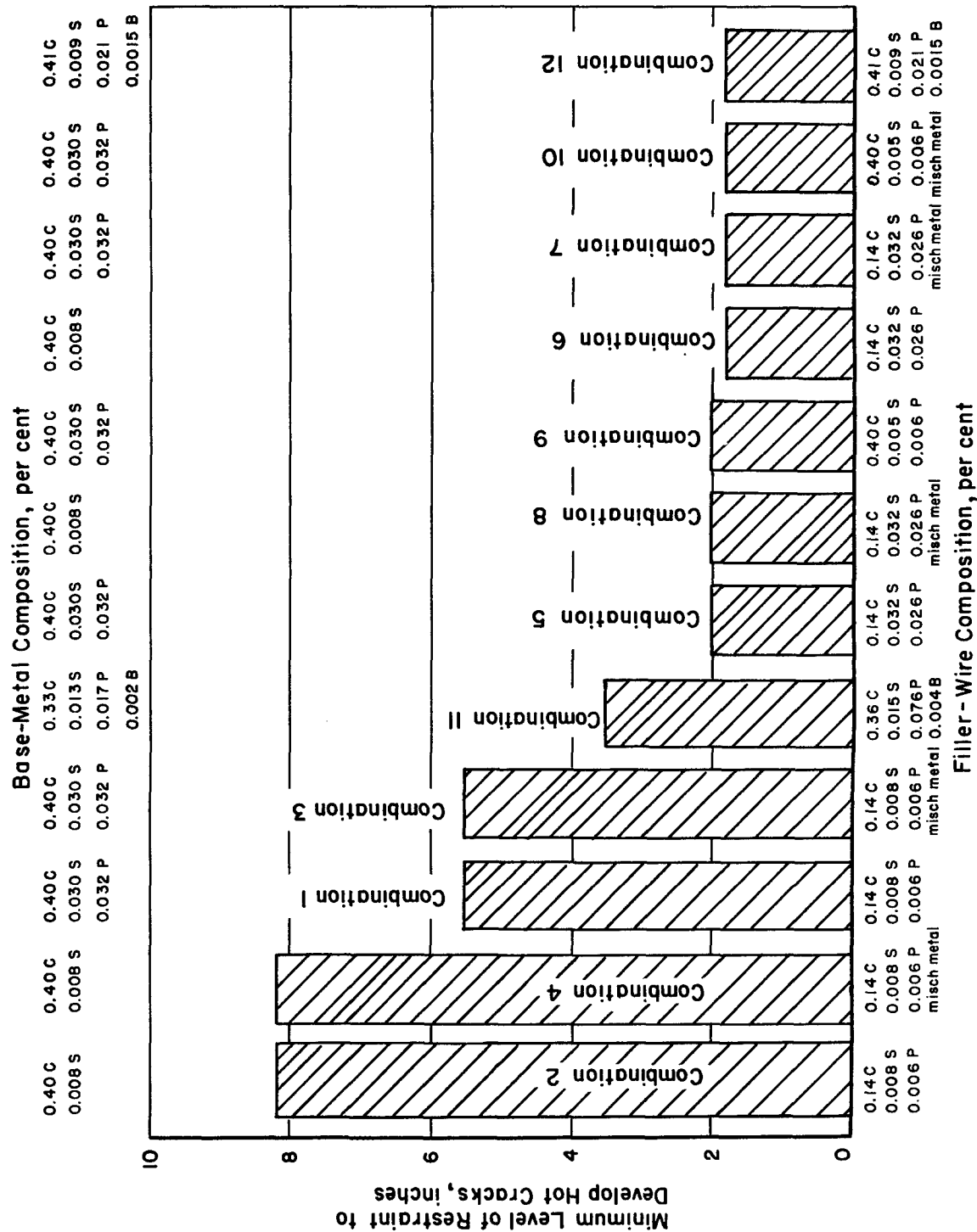
FIGURE 14. RESISTANCE OF VARIOUS FILLER-WIRE BASE-METAL COMBINATIONS TO WELD-METAL CRACKING

A-13966

The results of restrained weld-cracking tests are in satisfactory agreement with hot-tension data. For example, decreasing sulfur and carbon contents and a misch metal addition all tend to increase hot ductility and resistance to hot cracking. However, the effects of a decreasing sulfur content and a misch metal addition on hot cracking (Figures 11 and 13) seem to be more striking than the effects of these variables on hot ductility (Figures 3, 4, and 5). The effect of phosphorus on hot cracking requires further study in restrained weld tests.

Circular-Groove Tests

Cracking tests were made with the specimen shown in Figure 15. This specimen is far less expensive to prepare than the restrained weld specimen (Figure 9). The heats investigated are listed in Table 6, which also shows the test results. Two tests were conducted on each of four heats (Heats 4, 9-A, 10-A, and 3), and one test was conducted on Heat 9-B. According to the restrained weld tests, these heats vary in cracking resistance from 2 inches or less (Heat 4) to 8 inches (Heat 10-A) of restraint (Table 6).

The inert-gas consumable-electrode process was used to deposit wire from the heats shown in Table 6 in low-sulfur commercial SAE 4340 steel base plate (Heat C in Table 3). Welding was accomplished under the same conditions used in the restrained weld tests.

The test results (Table 6) indicate that high-carbon low-sulfur phosphorus SAE 43XX (Heat 3) is the most crack resistant and high-sulfur phosphorus SAE 4340 (Heat 4) the most crack sensitive of the three SAE 43XX-type steel compositions. Results from the restrained weld tests showed that Heat 3 was slightly less crack resistant than Heat 10-A (low-sulfur-phosphorus SAE 4340). Test results of the circular-groove specimen show a greater difference in cracking resistance between Heats 9-A and 9-B than the difference in a misch metal addition seems to warrant. It is realized, of course, that further tests should be conducted before any definite conclusions may be drawn.

Compared with the restrained weld test, the circular-groove test seems to have two disadvantages. First, it is not so sensitive, because it did not give consistent results with the same filler wire and base-plate combination (Heats 9-A and 10-A). In addition, the test showed the high-carbon SAE 43XX steel (Heat 3) to be more crack resistant than the SAE 4340 steel (Heat 10-A). This type of behavior is not in agreement with past experience of carbon content versus cracking susceptibility. Second, the weld-metal cracks cannot be inspected to determine if they formed at a high or a low temperature. These disadvantages offset the advantage of cost; therefore no further circular-groove tests were conducted.
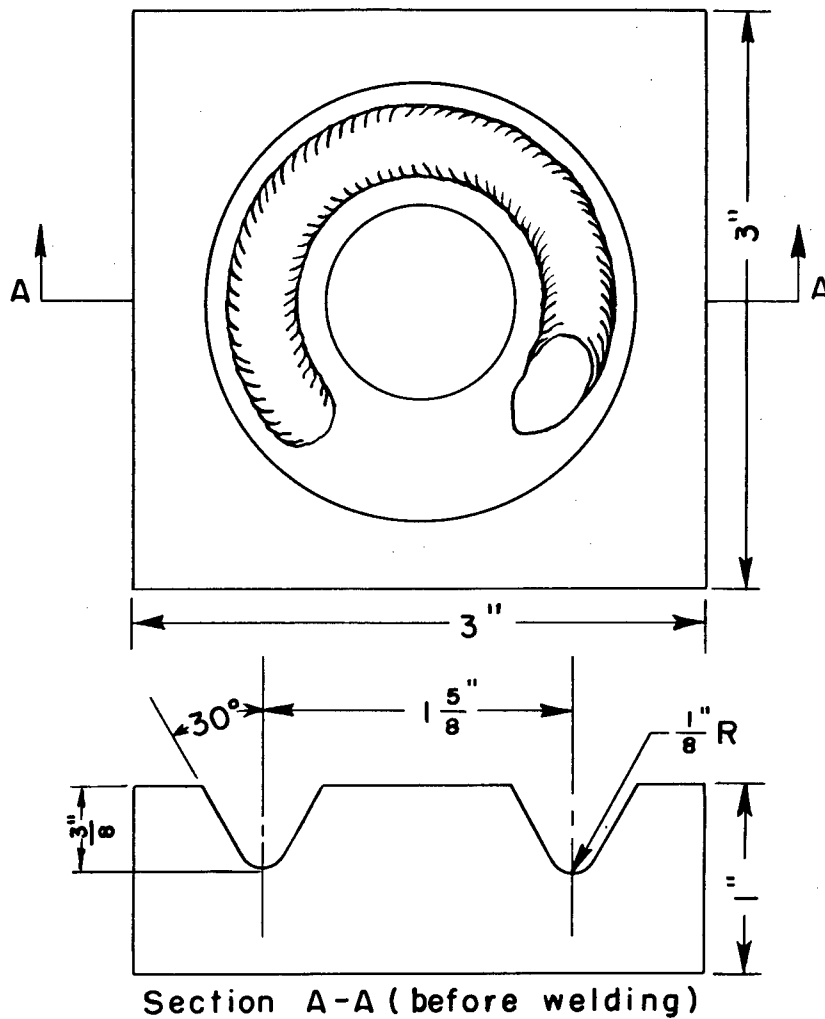
Section A-A (before welding)

FIGURE 15. CIRCULAR-GROOVE TEST SPECIMEN

A-1510

TABLE 6. RESULTS OF CIRCULAR-GROOVE, CIRCULAR-PATCH, AND RESTRAINED WELD-CRACKING TESTS

Heat(a)	Test	Length of Crack, inches	Average Length of Crack, inches	Cracking Resistance, inches Restrained Weld
		Circular Groove		
4 (high sulfur-phosphorus SAE 4340)	1	Entire length of weld		
	2	Entire length of weld	2-7/8	≤2
9-A (high sulfur-phosphorus 0.14% C)	1	1/2		
	2	2-1/2	1-1/2	--
10-A (low sulfur-phosphorus SAE 4340)	1	1/4		
	2	1-1/2	7/8	8
3 (high-carbon, low-sulfur-phosphorus SAE-43XX)	1	1/4		
	2	Crater crack	1/4	7
9-B (9-A plus misch metal)	1	Crater crack	--	--
		Circular Patch		
3	1	5/32		
	2	3/4	15/32	7
4	1	9/32	9/32	≤2
10-A	1	1/4		
	2	5/32	7/32	8

(a) Compositions shown in Tables 1, 2, and 3.

Circular-patch cracking tests were conducted for the same reason as the circular-groove tests. The primary reason was to be able to substitute an inexpensive specimen for the restrained weld specimen. The test results obtained with the substitute specimen should show good reproducibility and lend itself to examination of the crack surfaces after the tests are completed. The specimen is shown in Figure 16. It is a special modification of the circular-patch test. The geometry of the joint was modified for use with the inert-gas consumable-electrode process.

Three filler-wire compositions were studied. Table 6 lists the heat numbers and test results. All three heats were studied in restrained weld and circular-groove tests. Two circular-patch tests were conducted on Heats 3 and 10-A and one test was conducted on Heat 4.

Welding conditions were the same as those used for the restrained weld and circular-groove tests. The base plate for the circular-patch specimens came from the low-sulfur commercial SAE 4340 heat as did the circular-groove specimens.

The test results of the circular-patch tests (Table 6) indicate that this type of test is not sensitive enough to distinguish between a crack-sensitive steel and one that is not crack sensitive. This is shown from the results of Heats 4 and 10-A. Heat 4 is a high-sulfur and high-phosphorus SAE 4340 steel which from past experience would be expected to be more crack sensitive than Heat 10-A, which is a low-sulfur low-phosphorus SAE 4340 steel. The results of the circular-patch test did not indicate any appreciable difference in cracking resistance between the two steels. The restrained weld test indicated a great difference in cracking resistance (2 inches and 8 inches which are the lower and upper limits of the specimen) between the two steels. The performance shown by the latter specimen is in agreement with previous work on the cracking resistance of these steels.

To obtain more useful information from the circular-patch test, it appears that several tests should be made with each combination of filler wire and base plate and an average of the test results be used. To obtain more useful information from this test, the restraint offered by the specimen should be varied instead of depending on length of cracking as the criterion. By taking these modifications into consideration, the circular-patch specimen would not be any more inexpensive than the restrained weld specimen in determining the crack sensitivity of a weld metal. On this basis, no additional tests are planned in the investigation.
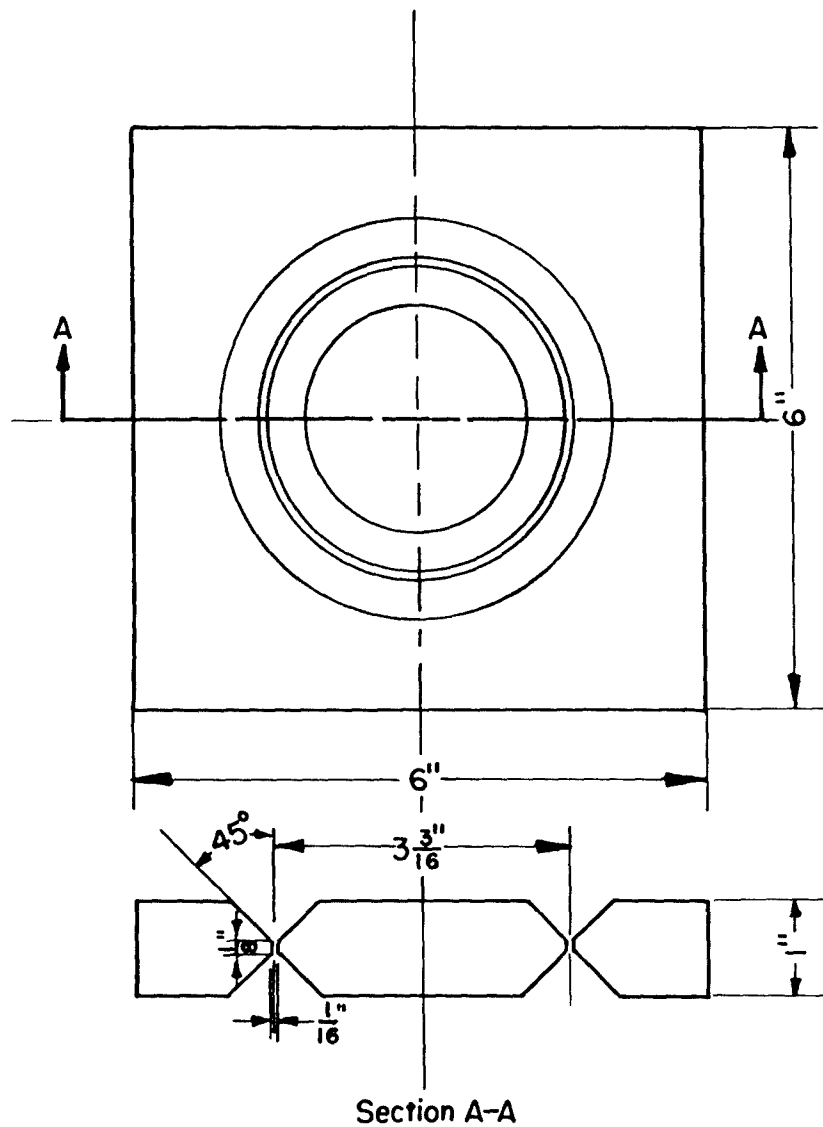
FIGURE 16. MODIFIED CIRCULAR–PATCH TEST SPECIMEN

A–10607

GENERAL DISCUSSION

So far, good correlation has been obtained between the results from hot-tension tests and restrained weld-metal cracking tests. This correlation has been quantitative as well as qualitative. For example, decreasing sulfur and carbon contents were shown to increase hot ductility and cracking resistance more than a misch metal addition. Yet the correlation has not been perfect, because sulfur had a greater effect on cracking resistance but a smaller effect on hot ductility than did carbon. It is expected that a perfect correlation is not needed to establish a fundamental relationship among composition, hot-tension properties, and weld-metal cracking resistance. The setting up of such a relationship would be an important step in determining the causes of hot cracking; it may be realized before the end of the next contract period.

FUTURE WORK

It is planned that this work will continue for another year. Future work for the next contract period will fall into three categories:

(1) Continuation of Hot-Tension and Weld-Metal Cracking Tests. The effects of phosphorus on hot-tension properties and cracking susceptibility will be studied in greater detail. Other residuals in high-strength steels will be studied also. These include silicon and nitrogen.

(2) Investigation of Low-Temperature or Cold Cracking in Weld Metals. This type of cracking has been encountered in the weld-metal cracking tests and was eliminated by using a 200 F preheat. Its elimination in other cases might require more information than is available. Therefore, cold cracking will be studied by either one of two means: (1) impact tests; or (2) tension tests in the temperature range from 1800 F down to room temperature. The basis for such an investigation is the belief that cold cracking occurs at a temperature when the weld metal has low notch toughness and ductility.

(3) Continuation of the Study of Nonmetallic Inclusions in Weld Metals. An intensive effort will be devoted to the location and identification of nonmetallic inclusions, especially intergranular eutectics in crack-susceptible weld metals. Microspectrographic analysis and radioactive isotopes will be used in conjunction with the light microscope, if necessary.